Methods for Interference Management in Medical Wireless Sensor Networks

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Abstract— Emerging Medical Body Area Networks (MBANs) require new, protected spectrum for clinical applications. This may mean uncoordinated and autonomous operation of multiple MBANs, within the new candidate bands. The question is that how will MBANs coexist as a secondary service with other radio systems? Clinical environment requires balance of robust and efficient wireless techniques to enable coexistence of MBANs and other radio devices where low transmission power MBANs as secondary systems may be vulnerable to interference from incumbent devices transceivers. Physical separation between the MBANs and incumbent radio devices and avoiding the transmission in the same frequency bands among the wireless techniques may be considered. In this paper, we propose interference management techniques considering such coexistence between the MBANs and other radio systems and deal with the issue of co-existence with primary systems by proposing novel methods for a gateway-to-gateway coordination, to assist the methods described in the first and second part of this paper. Result is improved reliability and Quality of Service for MBANs. These would lead to multiple clinical benefits, including better patient mobility, more monitoring flexibility and extension of monitoring into care areas that are currently unmonitored. Reduced clinical errors and reduced overall monitoring costs are other results.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) emerge as a dominant technology affecting many aspects of human life [1-12], [14-17]. Wireless network of sensors around a patient in a hospital or medical ward provides multiple clinical benefits

including patient mobility, monitoring flexibility, extension of monitoring into care areas that are currently unmonitored, reduced clinical errors and reduced overall monitoring costs [2]. Body worn sensors may include various sensor types on single patient body. They require a capability to add or remove fast from the patient body. On an individual basis, they include the bit rates of 1-2 kbps per patient and on an aggregate basis they may require 10 kbps bit rate. For wireless sensor networks, the connectivity may extend itself to 1 meter to gateway (GW). Medical WSN applications are mission critical applications for clinical environment. Robust wireless link for bounded data loss and bounded latency, capacity for patient and sensor density, coexistence with other radios, battery life for days of continuous operations and small form factors for body worn devices, among the medical WSN or MBAN requirements. These requirements can be satisfied through the utilization of the techniques such as the diversity and error control in time and frequency domain. These techniques include the Forward Error Correction (FEC) and the Adaptive Repeat reQuest (ARQ), low duty cycle Time Division Multiple Access (TDMA) for sensor information rate, and more efficient small antennas [2]. In this paper, we propose interference management techniques to improve the wireless link for coexistence of the MBANs and the other radio incumbent systems. The remainder of this paper is organized as follows. In the next section, we will first describe the problem and provide the background information on the existing methods for the interference management in WSN. Then the methods for a fast and dynamic semi-distributed interference management and radio channel allocation in the wireless sensor networks will be described. We present the methods for a centralized fast and dynamic interference management in wireless sensor networks; and also outline methods for Gateway-to-Gateway coordination, for interference management, in wireless sensor

networks in the second and third parts of this paper, before we finally discuss the simulation results and conclude the paper.

II. THE PROBLEM OF INTERFERENCE MANAGEMENT IN MEDICAL WIRELESS SENSOR NETWORKS: BACKGROUND

The merging MBANs require new, protected spectrum for the clinical applications. Potential radio bands include the unlicensed bands, 400 MHz MedRadio and the Wireless Medical Telemetry System (WMTS) band. While the unlicensed bands lack reliability needed for unprocessed life critical monitoring data, they are usually fully utilized by the hospital WLAN for the mission critical applications [2]. For the 400 MHz MeRadio, the duty cycle forces MBAN to operate within the 3 MHz centre of the MedRadio, considering the fact that 3 MHz is insufficient for Medical MBAN population within hospital. The WMTS band on the other hand consists of the limited and disjoint spectrum bands which are heavily utilized by hospital for existing telemetry applications. Therefore recently Federal Communications Committee (FCC) began rulemaking to establish a new MedRadio service for the Medical Radio Communications Devices [2].

Figure 1 shows the 2360-2400 MHz bandwidth which is a suitable candidate as it permits small and efficient antennas and also allows high symbol rate (modulation bandwidth) for low duty cycle and short bursts of data. Furthermore, the existing Incumbent Aeronautical Telemetry and Amateur operations are good candidates for coexistence with MBANs.
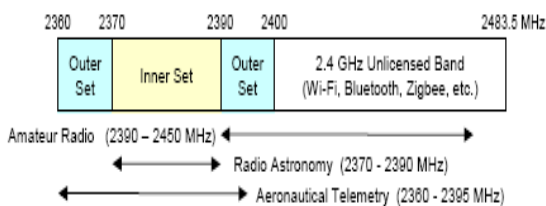

Figure 1 Candidate Radio Spectrum Band for Medical BAN [2]

As shown in Figure 1, allocating an extra 20 MHz bandwidth to the MBAN applications, would realize a secondary use at the health care facilities, after avoiding the frequencies in use by the incumbent services. This would ultimately mean an uncoordinated and autonomous operation of multiple MBAN devices within the candidate 40 MHz bandwidth [2]. The major question is that how will the MBANs coexist as a secondary service with the other incumbent radio services? The clinical environment requires a balance of robust and efficient wireless techniques to enable the coexistence of MBANs and the other radio devices, where MBANs, as secondary systems, with low transmission power, vulnerable to the interference from incumbent devices transceivers. The physical separation between the MBANs and the incumbent radio devices and avoiding the transmission in the same frequency bands, among the wireless techniques may be considered.

Interference management and its impact on wireless sensor networks has been focus of some of recent research activities worldwide including [7], [12], and [14-15]. In [4, 5], Minimizing inter-cluster interference by self-reorganizing Medium Access Control (MAC) allocation in TDMA based sensor networks is considered. In [12], authors present an interference-minimized multi-path routing technique with congestion control in wireless sensor network, for multimedia streaming. In [14], the methods and mechanisms have been presented to defend the wireless sensor networks from the jamming attacks while in [15] a performance study of the coexistence of the WSNs and WLANs is presented. Although in [14], the methods for interference management in WSN considered, the environment taken into account is a hostile jamming environment, which makes a cooperative approach involving the interfering RANs almost impossible. In almost all the cited references in literature, the proposed ideas are generic, without giving specific consideration to the emerging Medical BAN applications, their new coexistence requirements, their priorities and the high reliability requested.

In this paper, we propose the interference management techniques for such coexistence between the MBANs and other radio incumbent systems. Recently IEEE Standard study groups have outlined the technical requirements for emerging MBAN and BAN standards [1, 6]. Among them interference management has been highlighted as a key enabling technology contributing to a better Quality of Service (QoS) across the wireless sensor network, better energy consumption and most important of all a higher reliability for IEEE MBAN. Within the motivations presented in BAN or MBAN standard requirements, it has been mentioned that the sensor devices must be able to sustain an appropriate level of co-channel and out-of-band interference to be able to co-exist with other MBANs or BANs and even high transmission power systems such as the Wireless Local Area Networks (WLANs), in the crowded places such as hospitals. The fast and dynamic allocation of radio sub-channels would lead to an efficient exploitation of the available radio sub-channels and traffic variations, leading to the required sustainability of interference level by IEEE standard bodies. This is especially important for MBAN applications, which require a very high reliability of service. It is worth noting that the interference considered may be co-channel, in-band or out-band interference. In order to have the highest efficiency of the interference mitigation, the optimum dynamic channel allocation must be performed in "ms" time scale and below. A distributed interference

management scheme within a piconet, consisting of some cells and number of wireless sensors and their associated Base Station (BS) or sink (i.e. the data gateway to receive the information from the surrounding sensors), makes sense as it means no or very few interactions with a centralized entity, which would lead to a low cost circuit and low overhead signaling for wireless sensors. Since the transmission range of wireless sensors is usually limited to a few meters, it is safe to assume that the localized decision on the interference mitigation is an attractive option. Having said that there are two problems associated with such a fully distributed and sensor autonomous scheme in a wireless sensor network. The first problem is that the autonomous decision on the interference mitigation, may lead to a high required processing power and high complexity. The other problem is that any change in the radio channel allocation and the interference management decision in one sensor in one cell, may lead to an adverse impact on other sensors' decisions in the same cell or the cell close-by. So it seems that a collective decision in a centralized entity is a better way forward as the centralized decision making entity, which is aware of all the sensor nodes and will take care of most of the calculations related to the interference management leaving sensors with the low complexity and a low cost circuit. Such a centralized entity can avoid the conflicting situations, where the multiple wireless sensor entities within the different cells or the neighboring BANs may show interest in certain radio sub-channel and occupy it, leading to a catastrophic increase of the interference within that specific wireless sensor communications sub-channel. Despite this advantage, as mentioned above, a centralized dynamic channel allocation algorithm would eventually suffer from a high signaling overhead, between the lower layers (i.e. sensors) and the higher centralized decision making entity. For a single centralized entity, under a mass sensor deployment, within a wide geographical area, this may be seen a major problem, due to the limited range of communications for the wireless sensors, as they would require multiple transmission hops to reach the centralized entity. So it seems a strong tradeoff exists between the required low complexity of the wireless sensors and the required complexity of the signaling overhead in such a network.

In the first part of current paper, dynamic semi-distributed mechanisms for interference management in WSNs (i.e. BANs and MBANs), is proposed to take advantage of both centralized and distributed interference management to improve the QoS, while keeping the complexity of the sensor low. The problem with a distributed approach is that under highly loaded scenarios, when traffic demand or sensor density is high across the wireless sensor network, many conflicts of interest would

be inevitable as the distributed entities are usually making these decisions without necessarily being aware of the decisions being made by other radio entities in surrounding cells or piconets. This is specially the case for a mass wireless sensor deployment. As a result, some sub-channels available for communications, by sensor might be overloaded and suffer from severe interference and drop of packet of data leading to an unacceptable level of QoS. Despite its advantages, it may happen that on some occasions the semi-distributed approach proposed in the first, would be unable to handle the heavily loaded scenarios where some specific radio sub-channels are on great demand by many cells and settling conflict without involving a centralized entity proves to be impossible, provided that a fast interface between the lower radio entities and a centralized entity is available. Therefore the second part of this paper focuses on a gateway-centralized solution, for interference management in the medical WSNs. The major contribution of the second part is the novel trigger mechanisms and the protocols to create an efficient interaction between the distributed and centralized interference management techniques. For sensors employed in medical WSNs, the transmission power is considered to be lower than the traditional radio systems such as Wireless LAN. This leads to one of the major problems faced by the medical WSN, including a Medical BAN. Due to severe interference, medical WSNs may fall victim to another wireless system with much higher transmission power as shown in Figure 2. The inter-system interference management in this case, will play a crucial role in guaranteeing the required QoS for the victim system, for example, a Medical BAN. Under such scenario, the problem is that on some occasions, the semi-distributed or the GW centralized interference management schemes, proposed in the first and second part, may not have full control on inflicted interference on WSN, coming from surrounding Radio Access Networks (e.g. W-LANs). The reason is that they can only control the sub-channel allocation in their own network and has no influence on other Radio Access Networks' (RANs') interference mitigation or sub-channel allocation strategies. In third part, we overcome this shortcoming by proposing novel and efficient methods for a Gateway-to-Gateway coordination, for an efficient interference mitigation and radio sub-channel allocation.

Part 1: Methods for Fast and Dynamic Semi-Distributed Interference Management and Radio Channel Allocation

In the first part, we describe the methods for localized, fast and dynamic interference management.
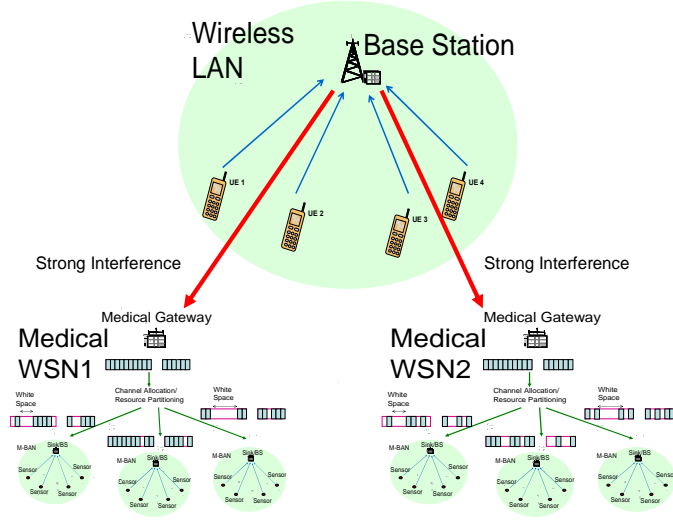

Figure 2 Interference inflicted on Medical WSN from a stronger wireless system

III. METHODS FOR FAST AND DYNAMIC SEMI-DISTRIBUTED INTERFERENCE MANAGEMENT AND RADIO CHANNEL ALLOCATION IN WIRELESS SENSOR NETWORKS

In this section, we first present the assumptions on our network and then formulate the problem with the interference:

The Model and Assumptions for the Medical Wireless Sensor networks:

We assume that number of sensors is assigned to a cell and communicate to a sink or base station. Sensors and sinks create a WSN (i.e. an MBAN or BAN) as shown in Figure 3. The medical sensor in Figure 3 may be responsible for crucial measurement, on patient's body: The sensor may measure a pulse rate. It may measure the body temperature, skin moisture, and blood pressure,
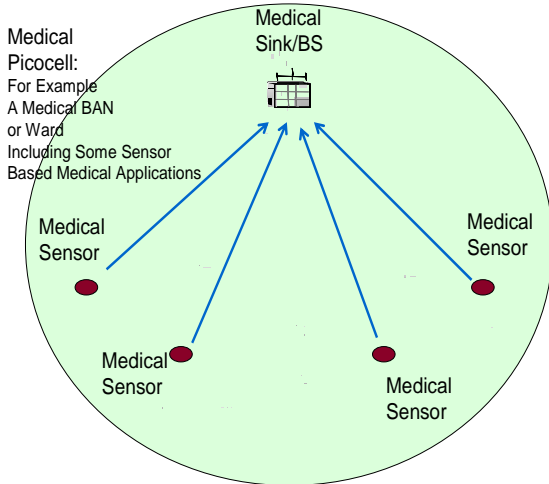

Figure 3 A Medical Picocell: Direct communications between the sensors and sink/base station:

Electrocardiography (ECG) signal or blood chemistry or even may be applied for glucose control and medicine administration.We assume that the radio network consists of J sink nodes communicating with their associated sensors. These sink transceivers are fixed or mobile. They are distributed uniformly in a square region of dimension $L \times L$. It is assumed that the radio sub-channels are shared between the sink transceivers, and if the two transceivers choose the same radio sub-channel, it will have some impact on both depending on the radio channel between them. It has been assumed that the sink transceivers have the capability to listen to the sub-channels and measure the interference receiver from the other transceivers on each available radio sub-band.

We assume that the N BAN or MBAN sinks form a cluster of transceivers. It is assumed that each cluster of sink/SINK has an assigned leader. Overall available spectrum has been divided into P sub channels and each sink might transmit at each time in M sub-channels so that $M<P$.

The Interference: The Mathematical Model and the Problem Declaration

We assume that the interactions between the involved sink transceivers can be characterized by the following interference function:

$\omega(i, j, S_m) = 1$ if sinks/transceivers i and j are both transmitting over the m-th sub-channel S_m (1)

else $\omega(i, j, S_m) = 0$

The interference from sink i on the sink j at radio sub-channel S_m can is assumed to be:

$$I_{ijm} = p_i \eta_{ij} \omega(i, j, S_m) \qquad \text{where m=1..M} \qquad (2)$$

where M is the number of radio sub-channels, p_i is the transmission power, associated with the sink or the transceiver i and η_{ij} is the overall transmission gain associated with the link from the sink transceiver i and sink transceiver j. In a similar way, the interference from inflicted on sink transceiver i by sink transceiver j is expressed as

$$I_{jim} = p_j \eta_{ji} \omega(j, i, S_m) \qquad \text{where m=1..M} \qquad (3)$$

The overall interference γ_i received from all the other sink transceivers can be determined as

$$\gamma_i = \sum_{j=1, j \neq i}^{N} \sum_{m=1}^{M} I_{jim} \qquad (4)$$

The overall interference β_i inflicted by sink i, on the other base stations can be determined as

$$\beta_i = \sum_{j=1, i \neq j}^{N} \sum_{m=1}^{M} I_{ijm} \qquad (5)$$

The total interference inflicted on all the sink transceivers within a cluster can be expressed as

$$\theta = \sum_{i=1,i\neq j}^{N} \sum_{j=1,i\neq j}^{N} \sum_{m=1}^{M} I_{ijm} \qquad (6)$$

We assume that the total traffic loads handled a sink transceiver is:

$$\alpha_i = \sum_{k=1}^{K} d_{ki} \qquad (7)$$

where d_{ki} is the amount of data, currently residing in the k th buffer of the i-th sink or base station. To have the SIR determined in each base station, it is assumed that the received signal power in each BS i is S_i so that S_i, i=1,…, n and signal to interference ratio is defined as

$$SIR_i = \frac{S_i}{\gamma_i} \qquad (8)$$

Although the cluster members primarily have concerns about the interference from or on other cluster members, they may also consider the interference from outside cluster. The protocols for interference measurements are presented in Appendix A.

Scenario One, Dynamic Cluster Based Interference Management:

Each sink transceiver in the cluster is assigned with a sequence number. Assignment of sequence numbers to the cluster members, is performed by the leader sink and updated every time the involved sink stops transmission

Step1: The leader sink starts with the transceiver with sequential order one.

Step 2: The sink (with sequence number 1) determines α_i or the total data currently resides in its buffers to be transmitted.

Step 3: The transceiver then maps the α_i to a minimum number of required sub-channels M.

Step 4: If it is below the number of currently occupied sub-channels, it adopts the new lower sub-channels as M for transmissions.

If it is equal to the number of the currently occupied sub-channels, the same number of the sub-channels stands. If it is above the number of currently occupied sub-channels, the new number is adopted as number of sub-channels.

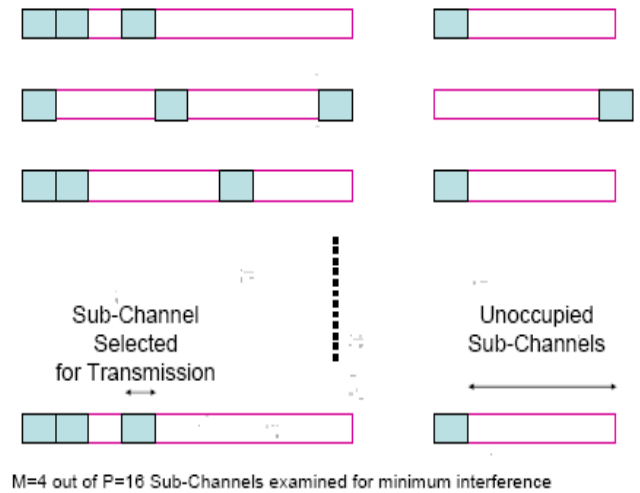M=4 out of P=16 Sub-Channels examined for minimum interference

Figure 4 Examining the sub-channels

Step 5: For new number of sub-channels, it listens (i.e. measures the current level of interference) to some, say G random or deterministic possible combinations of M out of overall available P sub-channels, as shown in Figure 4 to find out if the combination of M sub-channels out of P sub-channels that minimizes γ_i, the overall interference received from other transceivers. If the number of the sub-channels are not too high one possibility is to listen to all the channels and choose the M sub-channels with minimum interference first and then try the best say H number of combination of sub-channels, which are sorted in terms of the interference they receive in the increasing order.

Step 6: The sink asks the other sinks in the cluster to determine the current value of the interference they are experiencing in the selected specific combination of the sub-channels. It then determines how much this interference is going to be, for other transceivers, if it attempts to transmit in this selected combination of sub-channels. The intention is to perform these communications on a fast basis (say for example, in couple of ms have them completed), so that we can be able to take advantage of most updated information. These would ultimately mean On the Air (OTA) communications between sinks.

Step 7: Based on the outcome from the Step 6, it determines θ, the overall interference in the same selected combination of the sub-channels. It then compares the θ and γ_i to the previously recorded value of the interferences, for the same number of the sub-channels. If the values are less or the same, it considers the

θ and γ_i as the new recorded value and starts to transmit in this new combination of sub-channels.

Step 8: If all the cluster members have been examined go to Step 9, otherwise it is the next cluster member turn, go to step 2.

Step 9: When one channel allocation cycle for one cluster is completed, all the cluster members report their current interference level to the first cluster which attempts to determine the overall interference θ_f in the cluster.

Step 10: To maintain the fairness, rotate the order number so that the first sink transceiver is now the second transceiver. Go to Step 1 and start another channel allocation process with the next cluster. Please note that as the total inflicted interference is determined based on (6). Looking at (6) it can be seen that to calculate the interference, the sink or the leader needs the information about the current transmission power level and the path-loss from each sink to another. The path-loss metrics for sink, assumed to be already measured and stored in the sink memory as a matrix on an approximate basis, based on the methods explained in Appendix A. Therefore the only parameter to be updated is the current transmission power level in the sink.

Things are more complicated when the sensors forming the cluster are in the move. In this case, the power still is the only necessary parameter, but the problem is that due to the mobility of sensors the path loss parameter might change radically from time to time. In this case, a grid based mechanism is suggested as explained in Appendix A.

Please note that for above algorithm, the number of channels can be listened (e.g. ideal case is to monitor all the possible combinations), will decide the performance of the algorithm. Please also note that how much anticipation in advance we need to perform measurements, also will affect the performance and accuracy of the proposed algorithms. Figure 5 presents a summary of the proposed protocol.

One possibility is to reduce the number of measurements to rely on a direct exchange of the information between sinks. By exchanging the channel allocation information, the sink would be aware of the potential collision of interest and highly utilized radio sub-channels in close-by sinks or cluster of MBANS, and would not try to measure the combinations that have those highly occupied sub-channels included. This will ultimately save the time and efforts in the sink of interest.

Scenario Two: Merging the Clusters in critical conditions: We consider a scenario in which at Step 9 of scenario one, one cluster of MBANs realizes that its total interference or θ_f, is above a certain threshold of tolerance then the cluster can be declared as "red" as shown in Figure 6.
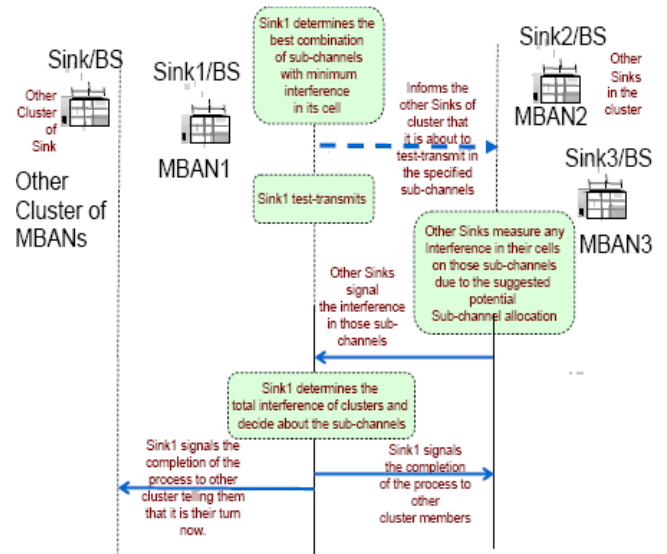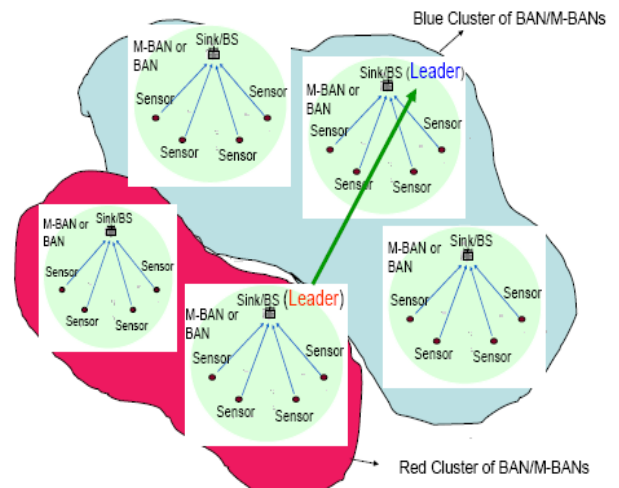

Figure 5 The proposed protocol

Figure 6 The leader of "Red" cluster asks the leader of the "Blue" cluster to consider a potential merger

The situation "red" happens due to the fact that the intra MBAN cluster level channel allocation is unable to deal with high level of interference.

The clusters that are not in a similar situation are considered to be in "blue" or low interference. In this case, the leader of the red cluster (i.e. in trouble) may ask the leader of the blue cluster to consider a merger to perform a joint radio sub-channel allocation process. When two clusters are about to join each other, the leader of one cluster informs other members of the cluster of the upcoming change and then triggers the process of the merger of the clusters as shown in Figure 7. Needless to say that the leaders of cluster already know that which one of the leaders is going to be in charge of the newly formed cluster (This can be a predefined assignment). The aim of the joint

distributed sub-channel channel allocation with extended cluster numbering, is to reduce the level of interference of the entire cluster to a blue situation as shown in Figure 8 by performing a new wider range dynamic sub-channel allocation by only one leader in charge.
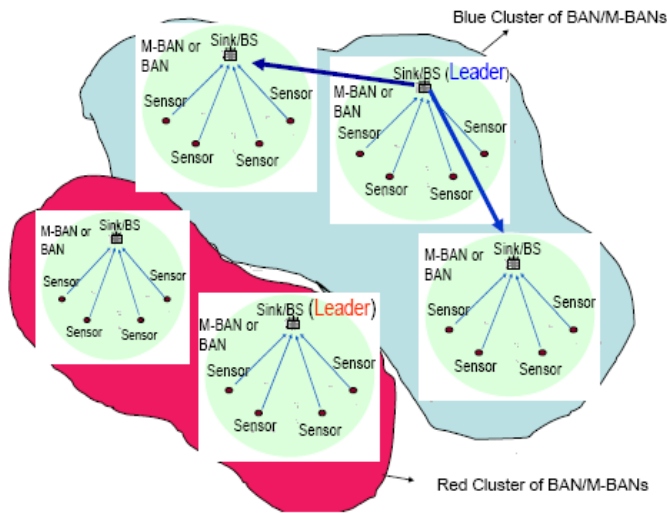

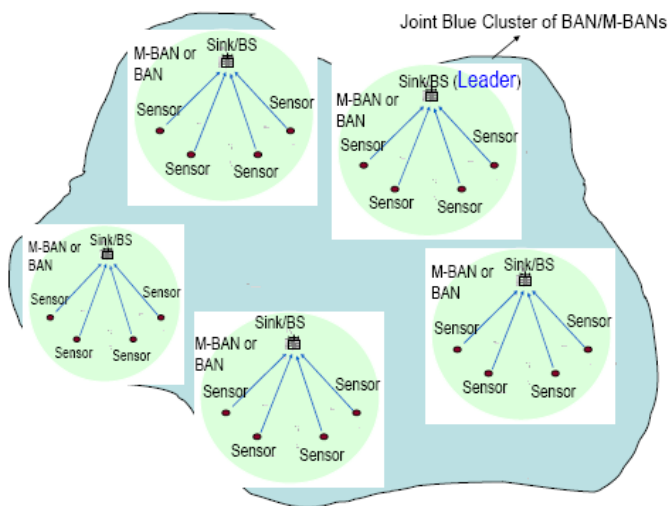Figure 7 Blue cluster leader informs all the member sinks of upcoming change

Figure 8 Transforming all the clusters into a blue cluster

To achieve that after the merger, the procedure would start from step one of the algorithms described above for the newly extended cluster, with more sink transceivers. It is worth noting that the main idea behind the merger is to make the other clusters aware of the situation with the troubled (in red) cluster and its critical interference management and radio channel allocation.

Scenario Three: Reducing the centralization effect by breaking down to smaller clusters

The situation described in Scenario 2, is only temporary. When the entire cluster is blue, the cluster may be split back to the original clusters' configuration. To avoid the centralization, extra signaling overhead to one specific leader and the excessive processing burden on the single cluster leader, after the merger, the leader of the joint cluster might ask former cluster leaders to examine their interference level. If all the former clusters are out of "red", the cluster leader would ask for breaking up of the clusters and giving the autonomous decision making capability back to the cluster leaders.

IV.   PERFORMANCE AND SIMULATION RESULTS

The simulations are carried out in MATLAB based on the mathematical models described above adopted from [9]. As shown in Figure 9, a random topology of MBANs consisting of four interfering sinks is considered. The results are theoretical only and no real measurement has been performed for these results. In terms of traffic, an extreme case is considered where all the transmitting sinks and their associated sensors are in transmission mode continuously. The Signal-to-Interference Ratio (SIR) has been calculated based on (8), therefore it is very generic model and captures the impact of packet latency or packet losses in an indirect way.

It is assumed that number of MBANs assigned to a cluster leader. It is also assumed that sensors transmit with the same transmission power. *It is worth noting that the white spaces and overall spectrum assigned to each sink will be controlled in time by its own cluster leader. This makes an independent exploitation of spectrum availability feasible especially in border cells.* Adaptive channel coding rates for a data packet and radio node have been considered to enable the radio nodes to adjust their transmission rates and consequently the target SIR values. The Bit Error Rate (BER) requirements selected for simulations, is 10^{-3}, and it is assumed that the Reed-Muller channel code RM(1,m), the coding rates combinations and the corresponding SIR target requirements used for our simulations, are similar to [9]. The results are depicted in Figure 9. For each sink transceiver, the narrow blue line bar represents the interference inflicted on other transceivers on current sub-channel, the red bold line bar represents the interference inflicted from other sinks in current sub-channel and finally INT2 represents the overall interference inflicted on other sinks from the sink of interest. It can be seen that how successfully the dynamic channel allocation process has managed to reduce the interference inflicted in each sink and the interference on other transceivers by each sink at sub-channel level, while in some cases, the transceiver has managed to occupy more radio sub-channels. In figures, diamond shape represents a potential MBAN.
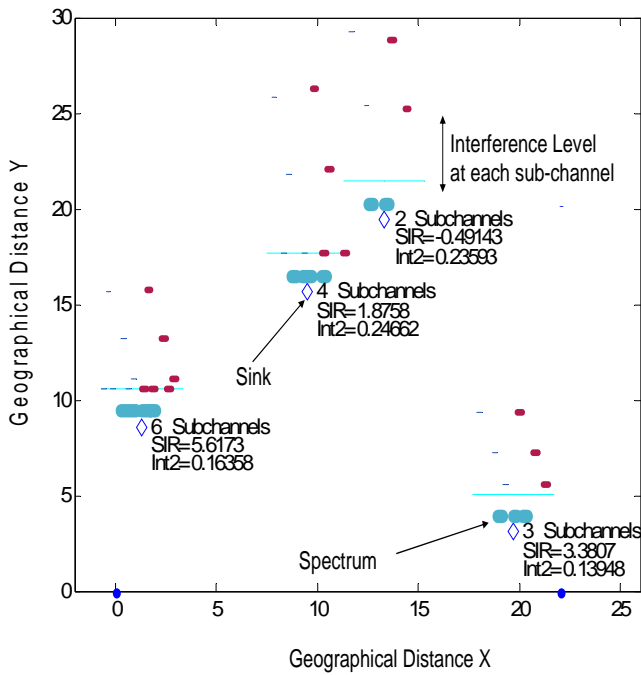
(a) Before completion of radio channel allocation process
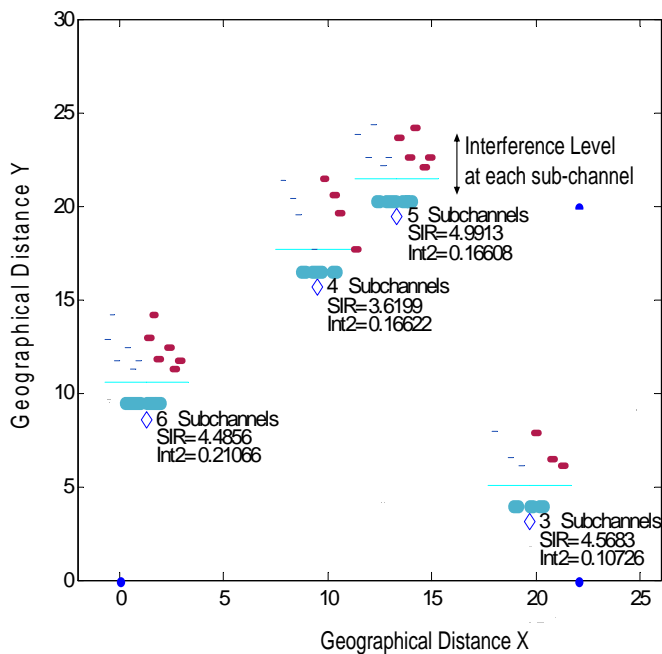
(b) After completion of radio channel allocation process

Figure 9 Results of the distributed and dynamic interference management and the channel allocation process

Part 2: Gateway Centralized Fast and Dynamic Interference Management in Wireless Sensor Networks

In this part, we describe the methods for gateway centralized fast and dynamic interference management in wireless sensor networks.

V. TRIGGERS FOR GATEWAY CENTRALIZED FAST AND DYNAMIC INTERFERENCE MANAGEMENT IN WIRELESS SENSOR NETWORKS

In this section, we assume that multiple MBANs coexist in a network of MBANs. They operate on an uncoordinated basis but with as we will explain, with some coordination regarding the interference management:

Triggers for Centralized Gateway Controlled Solutions for Mass Sensor Deployments

As explained before, there are situations where the proposed semi-distributed solutions in the first part would require further assistance. In what follows, we described these situations and present the trigger mechanisms for the centralized GW based solutions.

Trigger 1: Overwhelming number of conflicts in a mass sensor deployment scenario

As described in the first part, the medical WSN/BAN which has more interference than an acceptable threshold considers itself to be in "red" otherwise it would be considered in "blue". We consider the situation where large number of the clusters of WSNs (e.g. MBAN or BAN) is in "red" (i.e. high interference conditions) as shown in Figure 10. In this case, the clusters may be unable to merge further, due to the negative responses from the involved clusters, all employing the distributed protocol described in the first part. Another possibility is that a single leader sink simply either would be overwhelmed by number of potential communications to other leader sinks of other clusters of MBANs involved, or it will not be able to have access to all the involved sink leaders. In this case, we add a centralized gateway to such a mass deployment of MBAN as depicted in Figure 11. Each sink is assigned with number of radio sub channels by GW (piconet controller). In this case, as we will explain later that gateway will be in charge of settling down the conflicts between the involved WSNs (i.e. clusters of MBANs). Under such a scenario, the gateway centralized scheme is to reshuffle the radio sub-channels for better conditions, in terms of the inflicted interference.

Trigger 2: The joint clustering process reaches its maximum size and despite that it is still in red.

The second scenario is described in Figure 12, where the four different clusters use the dynamic sub-channel allocation proposed in the first part, to stay in blue status or come out of red.

Figure 10 Mass sensor deployment with many unsettled conflicts between the involved BAN/MBANs

Their second attempt fails and they agree for a joint clustering attempt. However even creating the joint cluster would not help the situation and consequently the entire cluster calls for a gateway centralized mechanism to be proposed in the next section.

Trigger 3: Initialization before the semi-centralized dynamic sub-channel allocation process: The third trigger is explained in Figure 13.

In this case, the GW centralized techniques acts as an initialization for the semi-distributed dynamic channel allocation process described in the first part. It creates a better starting point in terms of inflicted interference for each one of the future potential clusters. After a successful channel allocation process the centralized GW, gives a localized autonomous power and decision making capability to the clusters involved. The clusters involved have the privilege to start their own new dynamic localized dynamic channel allocation process with a much better and less troubled interference profile.
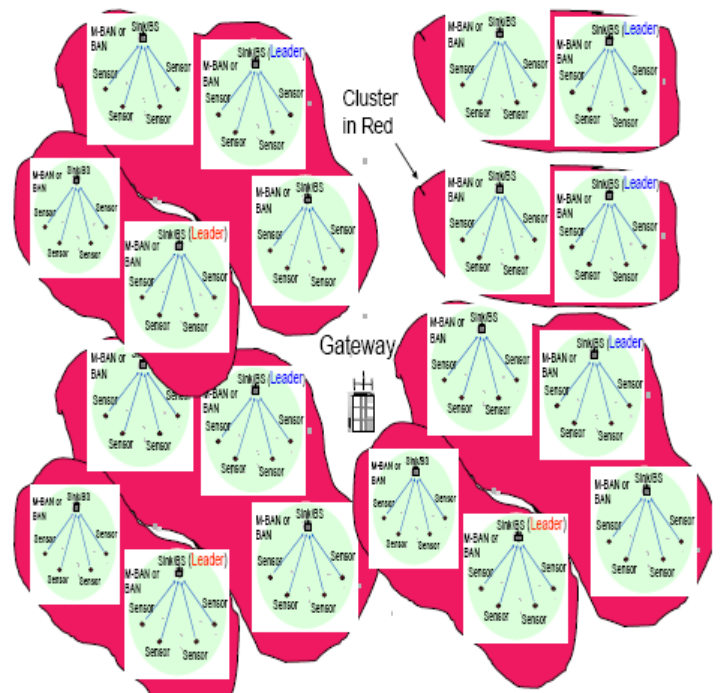
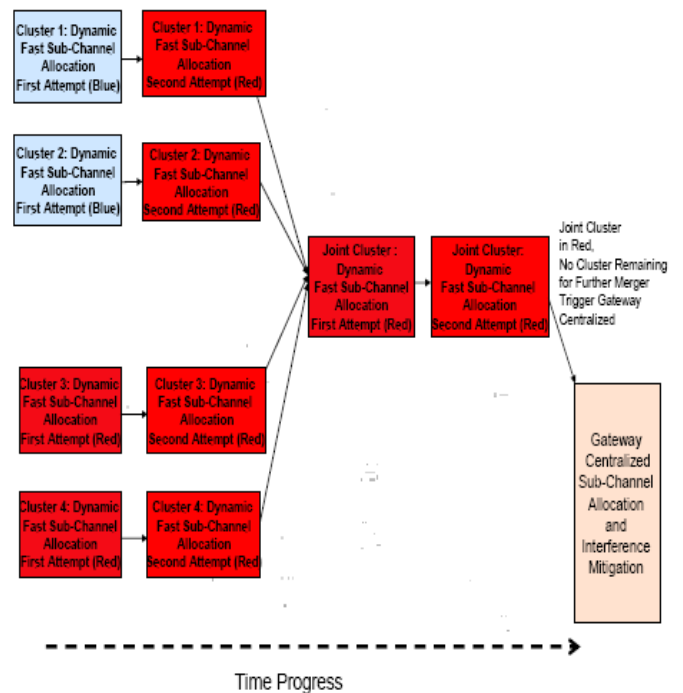

Figure 11 Group of BAN/MBAN controlled by the gateway

Time Progress

Figure 12 The Second Trigger for Gateway Centralized Sub-Channel Allocation and Interference Mitigation

VI. DESCRIPTION OF METHODS FOR GATEWAY CENTRALISED INTERFERENCE MANAGEMENT

Description of Centralized Algorithms

Step1: Gateway Requests for current transmission power, buffer occupancy and η_{ij} which is the overall transmission gain associated with the link from the sink transceiver i and sink transceiver j (The later one might be already available in gateway).

Step 2: The sink transceivers provide the requested information to GW.

Step 3: For each sink, the GW maps α_i to a minimum number of required sub-channels M.

Step 4: For number of sub-channels, considered for each sink, it takes into account the potential channel allocation for each sink. For example, for each sink a potential combination, of all the sub-channels is depicted in Figure 14.
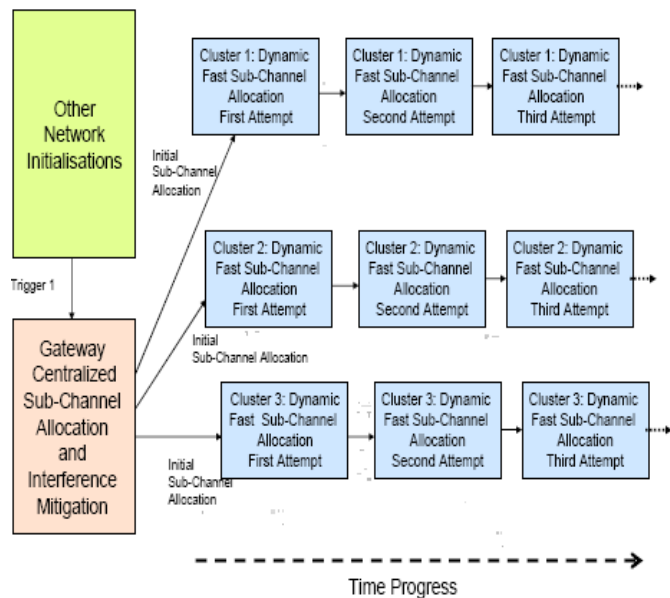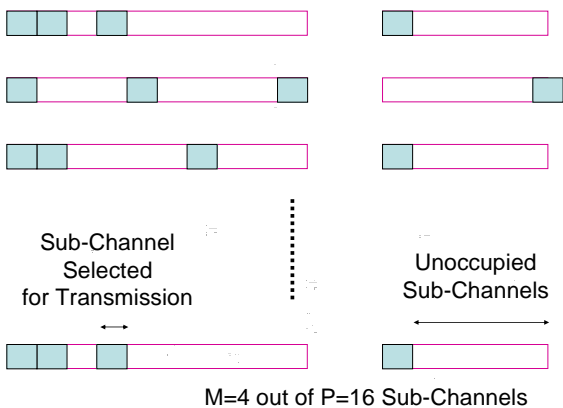
Step 5: Then the GW considers all or some of the possible combination of sub-channel allocations to sinks (e.g. on a random basis).

Step 6: Then Gateway takes into account the total interference inflicted on the entire sinks and selects the combination that minimizes θ in (6).

Step 7: Gateway lets the sink know about this initial sub-channel allocation as shown in Figure 15.

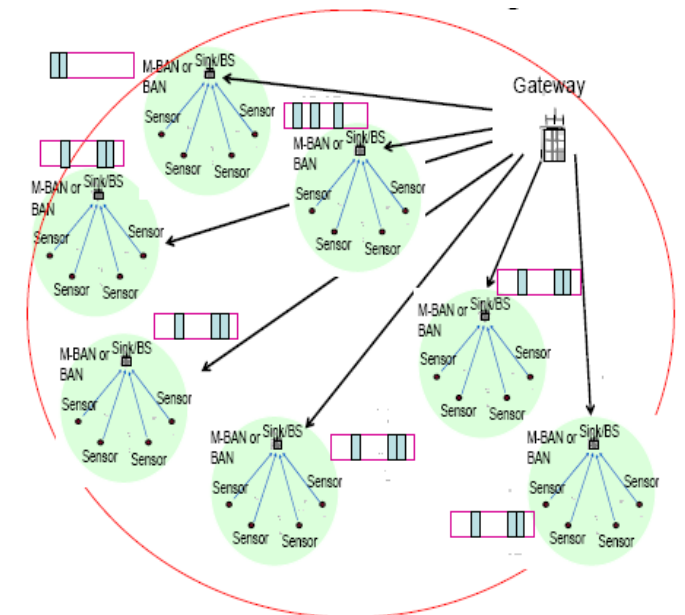Figure 13 Third Trigger for the Gateway Centralized Sub-Channel Allocation and Interference Mitigation

Figure 15 Gateway informs the MBANS

The proposed sub-channel allocation by gateway will be considered as an initial point of start for upcoming distributed dynamic channel allocations.

Please note that it is assumed that the transmissions will be carried out employing the old channel allocation, until gateway issues the new channel allocation. The transmitters then will resume the transmissions based on the newly issued channel allocation. The delay between the time of the detection of the problem (i.e. no more clusters are available to merge) and the time, the new allocation instruction reach the sink are decided based on four main factors:

1. Time required to communication between the sink 2. Time required for reconfiguration of the sink 3. Time to determine the best channel allocation in the GW 4.

The time allocated for communications between the GW and sinks, to inform them of the new channel allocation arrangement. In order to take advantage of the up-to-date information, the sum of these four delay elements is supposed to be rather short and no more than couple of radio frames

Figure 14 Examining the sub-channels

(Ideally no more than 10 ms). It is worth noting that the path loss and interference information required by (6), are estimated based on the methods explained in Appendix A.

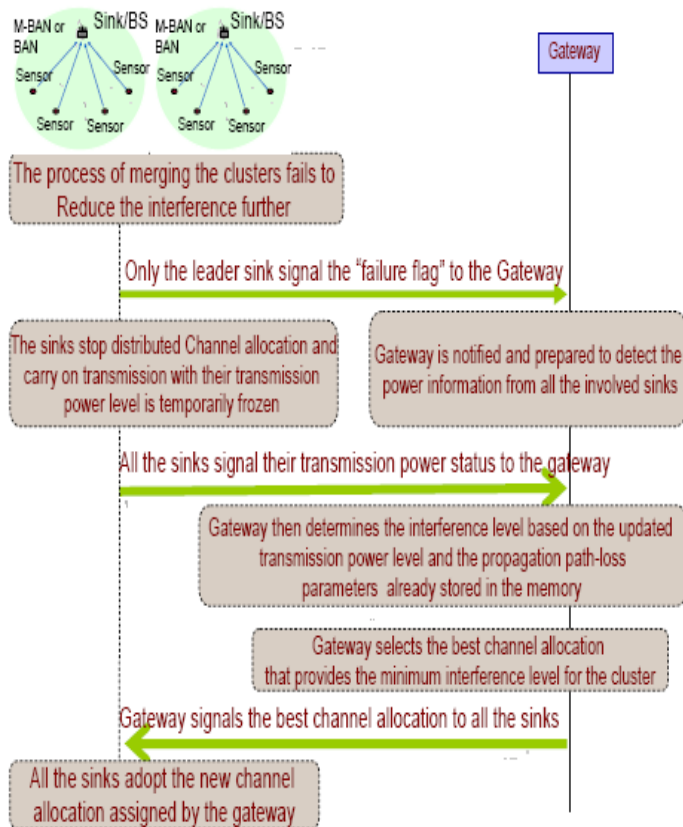The protocol described in Figure 16 summarizes the proposed algorithm, the functions and the required signaling:

Figure 16 Summary of Protocol for Centralized Gateway Controlled Solutions

## VII.   PERFORMANCE and SIMULATION RESULTS

Similar simulation conditions to part one is considered. The difference is that the topology consists of one gateway and four associated sinks.

The results depicted in Figure 17, shows how successfully the proposed gateway centered dynamic channel allocation process, has managed to reduce the interference inflicted in each sink of interest (i.e. MBANs) by the other sink transceivers, and the interference from the sink transceiver inflicted on others sink transceivers at sub-channel level. The total interference for a gateway has been monitored versus number of the attempted channel allocations possibilities. The results in Figure 17.c, confirms that almost after trying 400

potential channel allocations, the channel allocation algorithm has managed to converge to a minimum total interference value for current deployment of MBANs. In following figures, the diamond shape represents a potential MBAN.

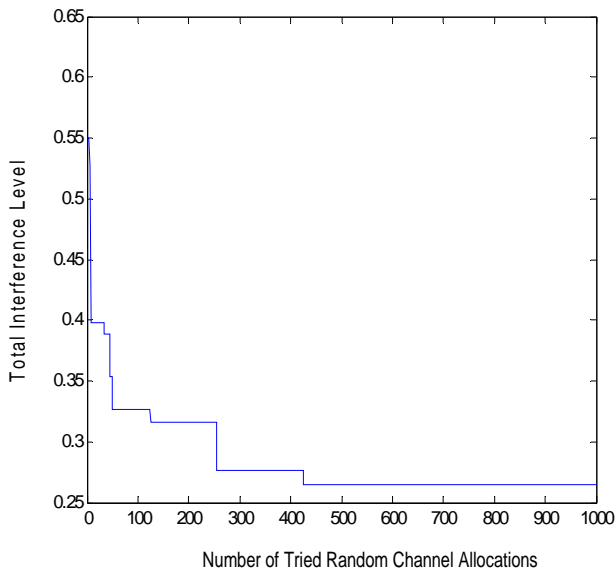Part 3: Gateway to Gateway Coordination for Interference Management in Wireless Sensor Networks

In the third part, we describe the methods for the gateway-to-gateway coordination, for the interference management.
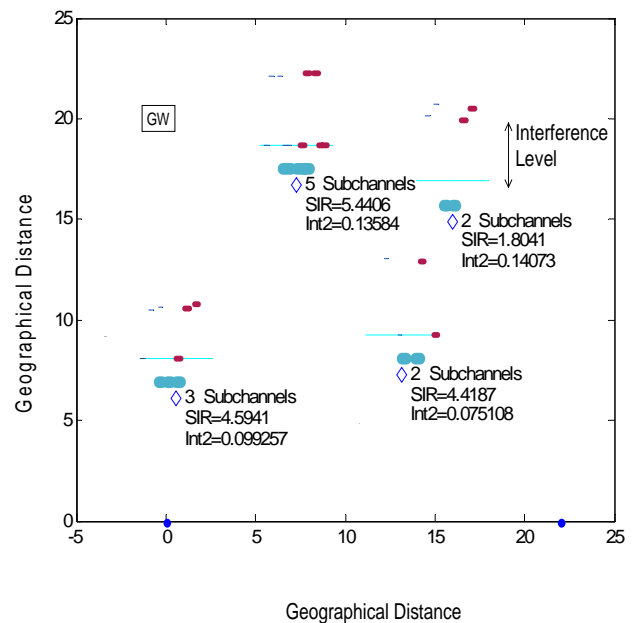
(a) Before completion of radio channel allocation process

and with one GW
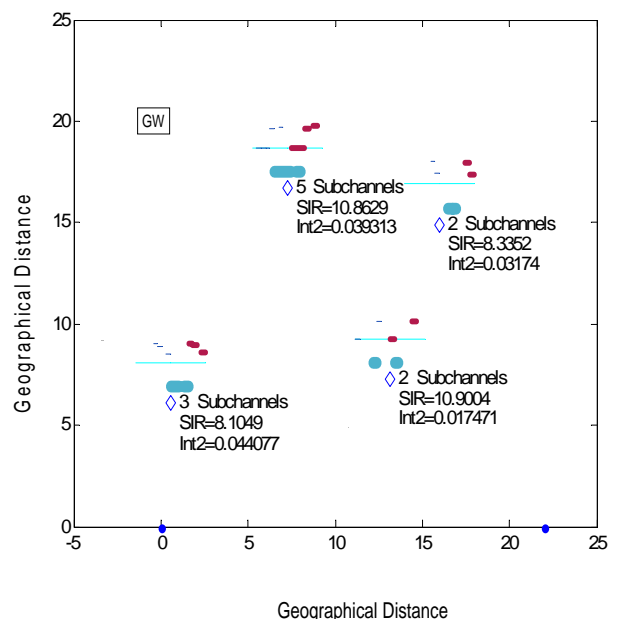
(b) After completion of radio channel allocation process

(c) Total interference versus number of tried random channel allocations

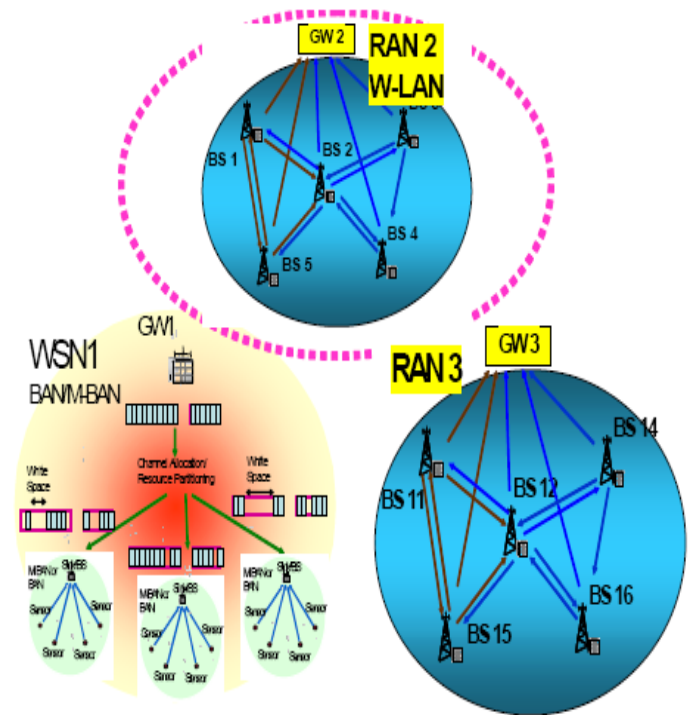Figure 17 Results of GW centralized interference management and channel allocation process

Figure 18 Problem with GW Centralized Interference Coordination, WSN in Red

Motivations/Triggers/Scenario for GW-to-GW Coordination, for an Efficient Interference Mitigation and Radio Sub-Channel Allocation

Figure 18 shows the situation after a potential GW centralized dynamic sub-channel allocation. The arrows represent the potential communications and the interfaces between the GWs and the sinks or the BSs.

It can be seen that while RANs assigned to GW2 and GW3 are in blue (low interference), the system assigned to GW1 (WSN consisting of MBAN) is in red, partially or fully (high interference). The situation is justified with the fact that the GW centralized channel allocation proposed in the second part, has no control over the dynamic interference mitigation or sub-channel allocation performed by other surrounding wireless systems (e.g. other radio incumbent systems). To explain the timing of this proposal, the following figure captures the event–triggered process, leading to the call of the coordination between the GWs proposed above:

Steps of the GW-to-GW Coordination for an Efficient Interference Mitigation and Radio Sub-Channel Allocation

Step1: GW1 determines the total interference θ, inflicted on sinks, served by this gateway based on the current interference level and the link gains.
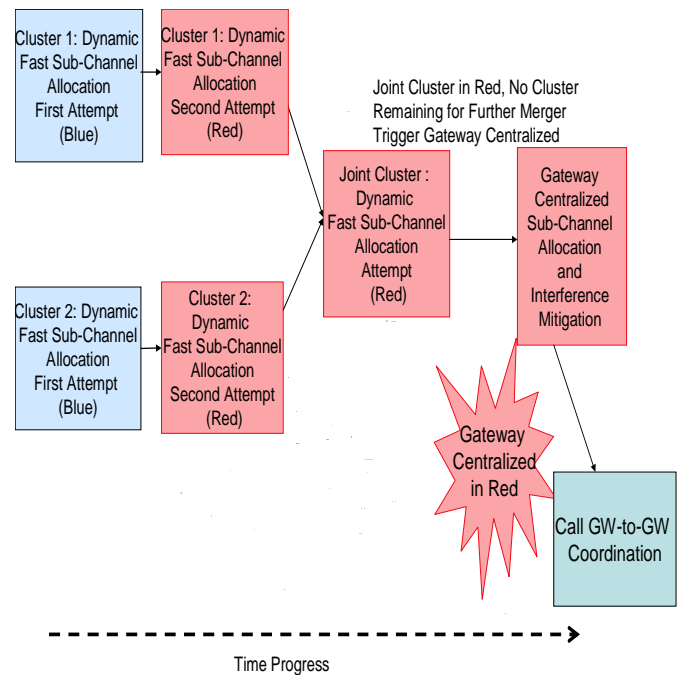

Figure 19 Trigger for GW-to-GW coordination

VIII.   DESCRIPTION OF THE METHODS FOR THE GATEWAY-TO-GATEWAY COORDINATION FOR INTERFERENCE MANAGEMENT

each time a major change of status in terms of interference is detected, or a GW-to-GW coordination is performed.

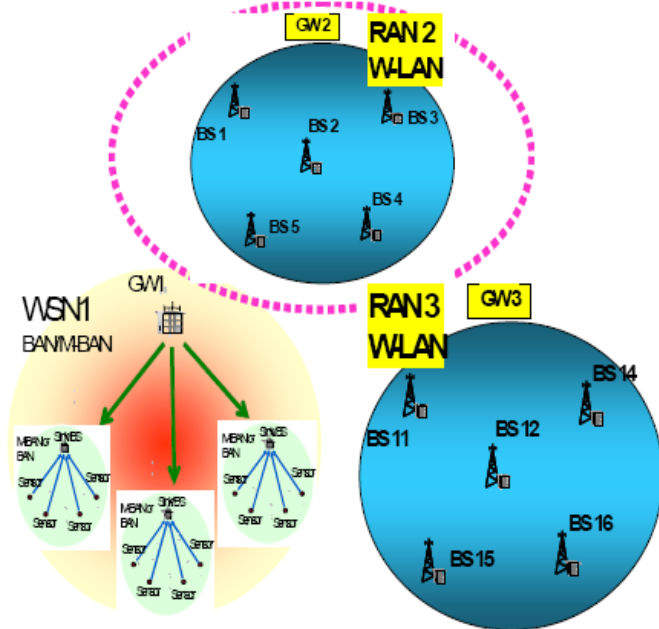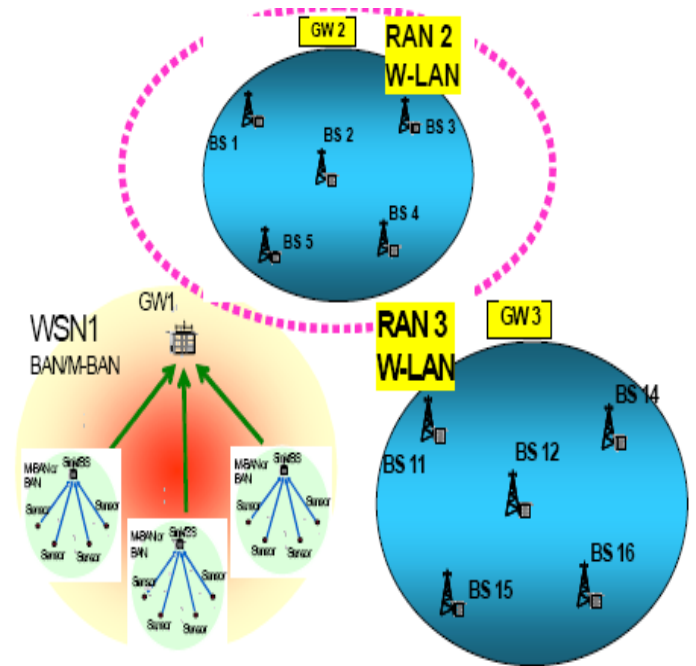Figure 21 Sinks provide the information related to the interference they suffer to GW

Figure 20 GW1 informs sinks to provide a measurement of the interference they suffer from

Step 2: As shown in Figure 20, the GW asks its assigned sinks to report their own interference measurement (or an indication of total interference in each sink).

Step 3: MBAN sinks provide this information to the GW1 as shown in Figure 21.

Step 4: GW1 of WSN compares the estimated total interference to the sum of all the interferences measured and reported by the sinks. If the difference is not significant GW assumes that the red situation is caused by an imperfect centralized dynamic channel allocation attempt. It performs further trials of the centralized dynamic channel allocation process, proposed in the second part.

The coordination is not required and the algorithm stops here. Otherwise we move to the next step.

Step 5: If the difference is high and above a pre-assigned threshold, GW concludes that the problem is coming form the neighbor systems (i.e. the other GWs from outside the medical WSN. In that case the GW1 asks its assigned sinks to report the consistently troubled sub-channels.

The troubled sub-channels as shown in Figure 22 are the radio sub-channels, which have suffered most from a consistently high amount of interference for say, past n transmission periods. The troubled sub-channel list is subject to an update,

Figure 22 Examining and Identifying the Red Sub-Channels

Step 6: The sink provides the requested information to the GW1.

Step 7: Based on the received list of the troubled sub-channel, the GW1 establishes a list of troubled sub-channels as shown in Figure 23.

Figure 23 GW identifies and forms the list of troubled radio sub-channels

The troubled GW1 informs the other GWs involved, that it is in trouble (i.e. red) and is suffering from their interference.

Step 8: GW 1 then provides the final list of troubled sub-channels to other GWs of other RANs (i.e. RAN2 or RAN3 perhaps two W-LANs in Figure 24) potentially inflicting the interference on the medical WSN.
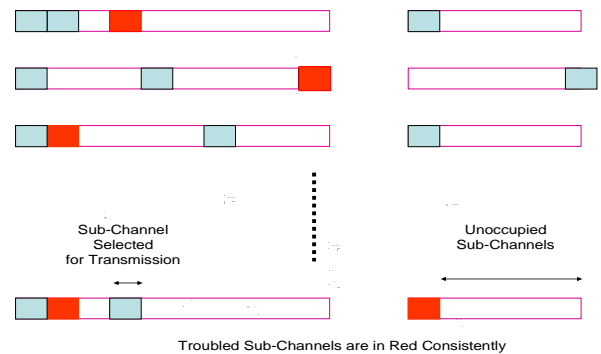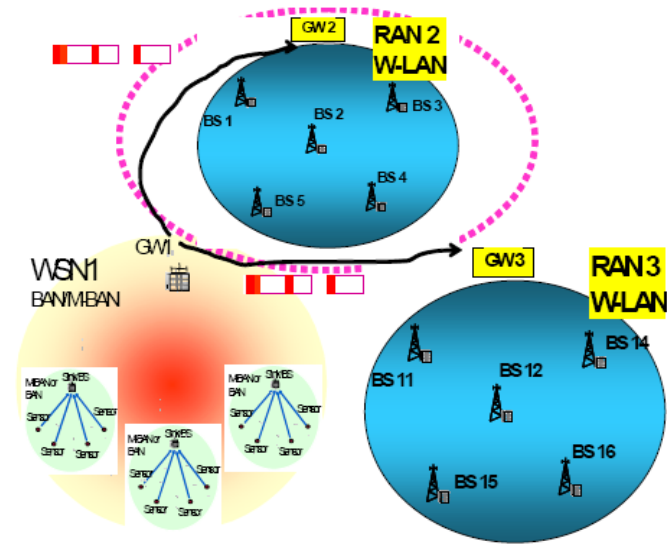

Figure 24 GW1 declares itself in trouble to other surrounding GWs

Step 9: Other GWs (for example, the GW2 and GW3 in figure above) perform new dynamic centralized channel allocation or interference cancellation, based on the knowledge of the troubled channels in the suffering GW.

Step 10: Other GWs (for example, the GW2 and GW3) require the current transmission power, current buffer occupancy and η_{ij}, which is the overall transmission gain associated with the link from the transceiver i and transceiver j (The later one might be already available in the GW).

Step 11: The BSs provide the requested information to the GW.

Step 12: For each of their BSs, the other GWs (for example, the GW2 and GW3) involved maps the α_i to a minimum number of required sub-channels M.

Step 13: For number of the sub-channels, for each BSs, other GWs consider the potential channel allocation for that BS.

Step 14: Then other GWs (for example, the GW2 and GW3 in the example presented above) consider all the possible combination of sub-channel allocations to BSs (e.g. on a random basis), avoiding all the red sub-channels in the list, provided by the troubled GW or avoiding the sub-channels that have negative impact on the red-sub-channels.

Step 15: If not possible to avoid the list of the red sub-channels or the sub-channels within their spectrum that might have impact on those red sub-channels, then other GWs consider all
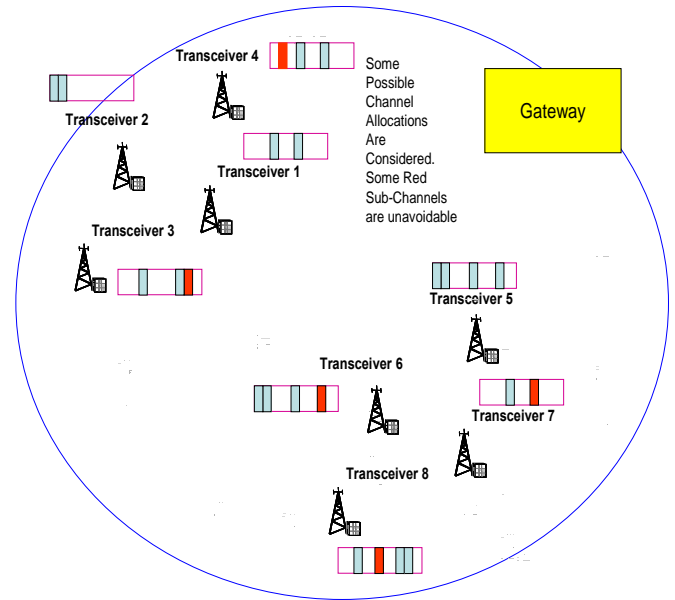
Figure 25 Gateway Examines the Potential Combinations Sub-channel Allocations

the combination of the sub-channel allocations to the BSs with minimum red sub-channels involved as shown in Figure 25.

Step 16: Then the other GWs consider the total interference inflicted on all the BSs, assigned to them and selects the combination that minimizes θ with minimum former red sub-channels involvement or minimum potential interference on the red-sub-channels

Step 17: Then the other GWs inform their own BS of their preferred sub-channel allocation, and the troubled GW1 of the completion of process.

The other stronger RANs (for example, the radio incumbent systems surrounding the MBAN), then start transmission in the new sub-channel configuration. Hopefully at this stage, the troubled GW is no longer in red. The proposed protocol is depicted in Figure 26.

When there is more than one troubled list as shown in Figure 27, the GW that receives the multiple troubled sub-channel lists, creates a new list by combining the received lists.

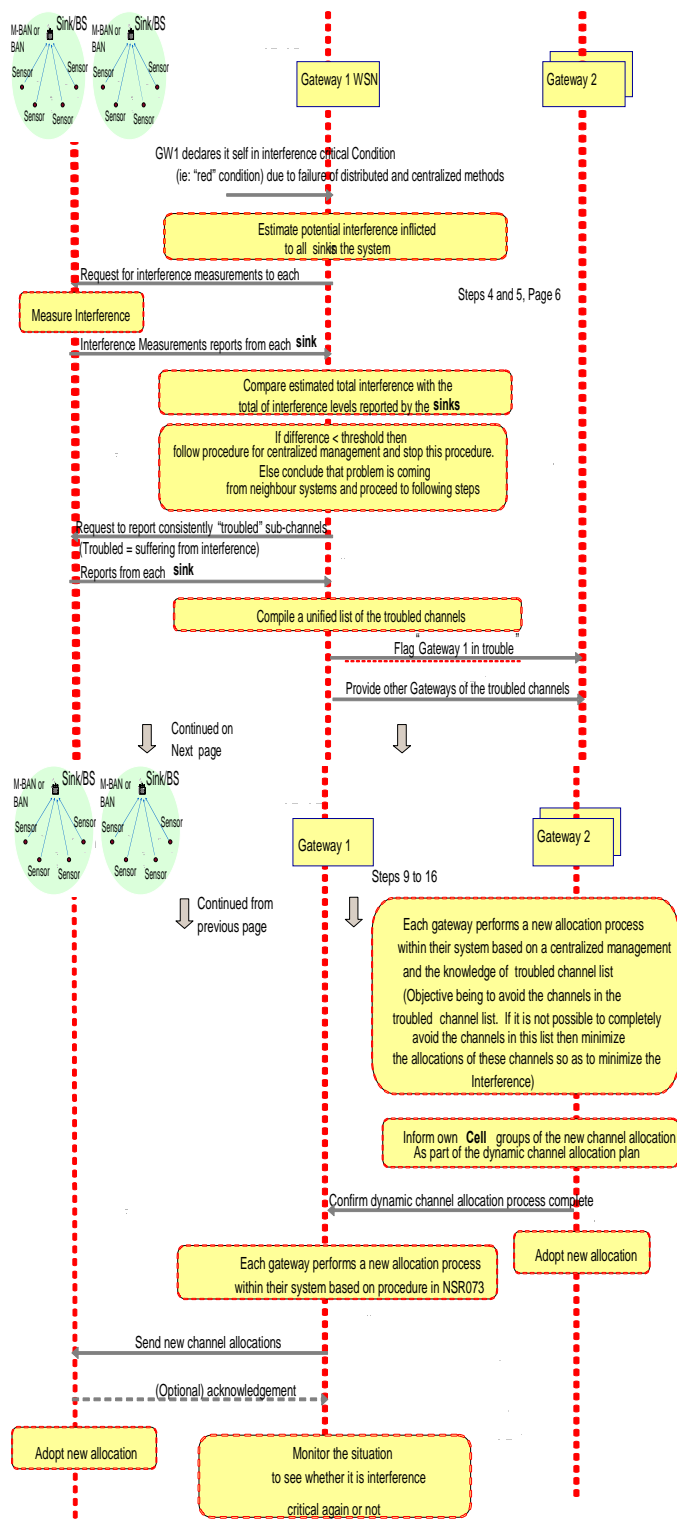give them a lower priority when it is about to perform the future dynamic channel allocation.

Sequence diagram (left column, Figure 26):

M-BAN or BAN — Sink/BS — Sensor ... | Gateway 1 WSN | Gateway 2

GW1 declares it self in interference critical Condition
(ie: "red" condition) due to failure of distributed and centralized methods

Estimate potential interference inflicted to all sinks the system

Request for interference measurements to each

Steps 4 and 5, Page 6

Measure Interference

Interference Measurements reports from each **sink**

Compare estimated total interference with the total of interference levels reported by the **sinks**

If difference < threshold then follow procedure for centralized management and stop this procedure. Else conclude that problem is coming from neighbour systems and proceed to following steps

Request to report consistently "troubled" sub-channels
(Troubled = suffering from interference)

Reports from each **sink**

Compile a unified list of the troubled channels

Flag Gateway 1 in trouble

Provide other Gateways of the troubled channels

Continued on Next page

M-BAN or BAN — Sink/BS — Sensor ... | Gateway 1 | Gateway 2

Steps 9 to 16

Continued from previous page

Each gateway performs a new allocation process within their system based on a centralized management and the knowledge of troubled channel list
(Objective being to avoid the channels in the troubled channel list. If it is not possible to completely avoid the channels in this list then minimize the allocations of these channels so as to minimize the Interference)

Inform own **Cell** groups of the new channel allocation As part of the dynamic channel allocation plan

Confirm dynamic channel allocation process complete

Adopt new allocation

Each gateway performs a new allocation process within their system based on procedure in NSR073

Send new channel allocations

(Optional) acknowledgement

Adopt new allocation

Monitor the situation to see whether it is interference critical again or not

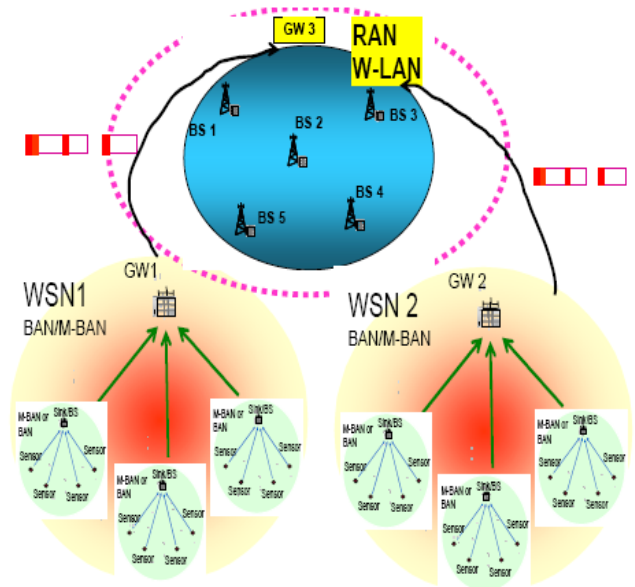Figure 26 Protocol for interference management based on GW-to-GW coordination

Figure 27 GW 3 receives the information of troubled sub-channels from two different WSNs (e.g. MBAN or BAN)

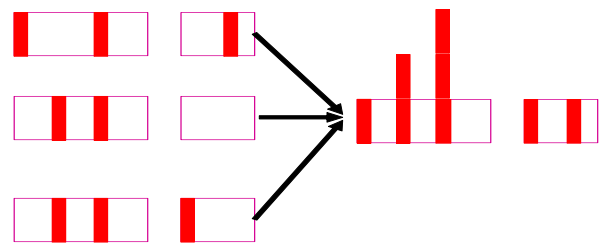Figure 28 GW 3 identifies and forms the list of troubled radio sub-channels

The combined list provides a prioritized list of troubled sub-channels as shown in Figure 28. It helps the stronger GW of interest (Wireless LAN GW3 for example, in Figure 27), to identify the most troubled (i.e. overlapped sub-channels) and

The GW 3 would then transmit the list of the combined (all or) most troubled channels to the BSs, who are about to be engaged in the process of dynamic channel allocation shown in Figure 28. The rest of the protocol is similar to the one described in Figure 26.

BSs assigned to GW2 would try to avoid these sub-channels as much as they can during the process of dynamic channel allocation.
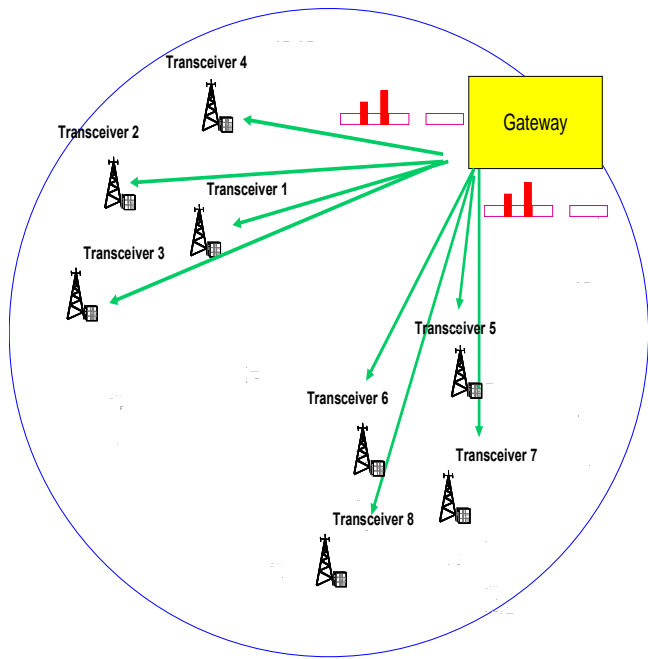
Figure 29 GW signals the most troubled sub-channels to its own BSs

IX. PERFORMANCE SIMULATION RESULTS

Similar simulation conditions to part one is considered. The difference is that the topology consists of two gateways and their associated sinks. It is also assumed that the sensors transmit with the same transmission power.

It is worth noting that the white spaces and the overall spectrum assigned to each sink will be controlled in time by its own cluster leader. This makes an independent exploitation of the spectrum availability feasible, especially within the border cells. The results depicted in Figure 30 shows how successfully the proposed gateway-to-gateway coordination process has managed to reduce the interference inflicted in each sink (i.e. MBAN) and BSs assigned to GWs. One issue with the proposed ideas in the third part of out paper is the fact that it might not be seen feasible for completely unknown RANs, without special modifications; like some common signalling middleware; to support the proposed protocol. Therefore in order to make the our proposed protocol applicable in real life application we propose to include the necessary signalling middleware for the radio incumbent systems, that are going to share the spectrum with the MBANs in future. When number of the involved interfering primary RANs is significantly higher

than the two GWs considered for current simulations, our further investigations confirm that the simulation gains are still significant although we have a drawback of extra communications overhead from the GW of the MBAN of interest (i.e. the victim system) to the surrounding interfering RANs. In this case, there is a trade-off between the gains achieved and the additional signalling overhead introduced.
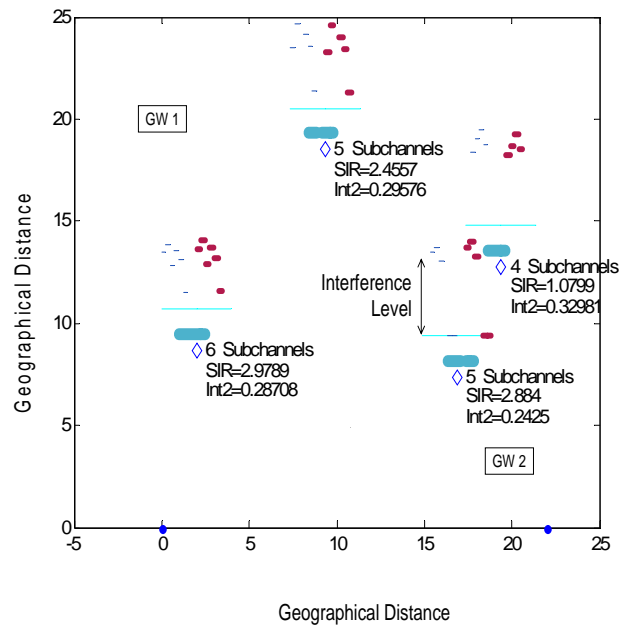
(a) Before GW-to-GW Coordination
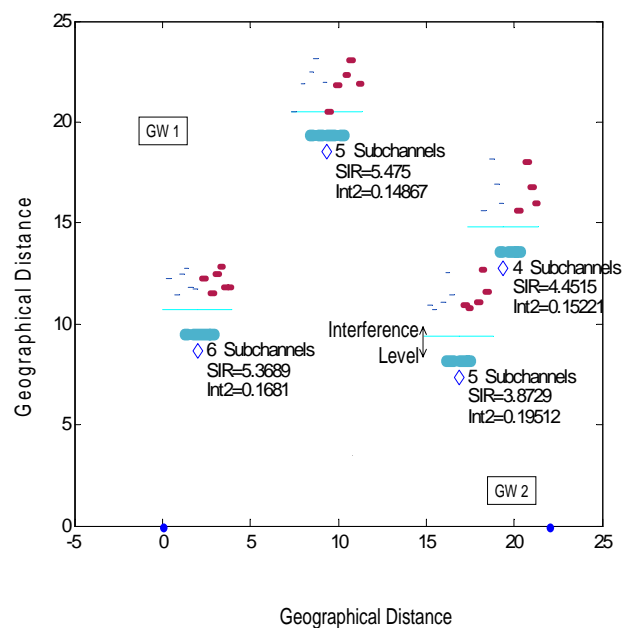
(b) After GW-to-GW Coordination

Figure 30 Results of GW-to-GW coordination for interference management and channel allocation process

X. CONCLUSION

Interference management is main focus of this paper, which is going to play a key role in creation of more capable and reliable Medical BANs. The proposed methods in the first part, avoid a permanent central entity for interference management and dynamic channel allocations.

It captures some features and advantages of cognitive radio while enjoying the advantages of traditional radio networks. Namely, the sink/transceiver which is currently responsible for the major part of the channel allocation process, in one phase, partially acts as a cognitive radio, when monitoring the sub-channels to come up with the best sub-channel combination for the future transmission. However in a cooperative manner the sink also has an eye on what is happening in the other cluster members which is a feature of traditional radio. As a result the process can be seen as a cooperative approach.

The outlined methods realize a fair cluster-wide dynamic interference management and channel allocations, guaranteeing low transmission overhead and low circuit complexity for sensors. There might be the cases when joint clustering proposed in current paper, is a favourite solution. However the solutions presented here (i.e. in the first part), may be considered as a localized ones. Due to the mass number of the deployed sensors in some cases, there would be many number of clusters of MBAN, specially for crowded places, such as a busy medical wards, where a single leader sink may no longer have the capability to handle the massive amount of signalled information and even if it is capable of that, it is not unable to reach those clusters of sensors located far away (without experiencing many transmission hops). In this case, we may already have many failing clusters of sensors in red. Under such a scenario, the second part of current paper proposes an alternative fully centralised interference management scheme, where regardless of the number of the conflicts it would provide assistance to the semi-distributed interference management solution proposed in the first part. Therefore we have provided the gateway centralized solutions for the medical wireless sensor networks. It is shown that the occasional activation and triggering of a centralized gateway-controlled fast and dynamic radio channel allocation, provides an efficient initial sub-channel allocation or a proper starting point for the upcoming distributed and autonomous dynamic interference mitigation and sub-channel allocations. This is to be considered also as an answer to the weaknesses of the distributed interference mitigation and dynamic channel allocations when they reach their limit or trapped in the conflicting conditions which can not be settled. Specifically when the cluster merging and sequential approach in the first part of current paper is unable to provide further improvement to the interference conditions, it asks for the intervening from the proposed simultaneous gateway-centralized fast and dynamic radio channel allocation in the second part.

The proposed methods exploit the fast variations of radio channel and the traffic load, in order to have better and more efficient interference mitigation and more efficient dynamic radio channel allocations leading to a significant interference reduction all over the network.

The proposed mechanism avoids the potential collision of interests in a distributed interference mitigation and dynamic radio channel allocation process involving multiple transceivers. It is shown that the proposed protocols are capable of improving the utilization of spectrum while universally improving the interference level.

The proposed methods in the second part are suitable for the situations, where the co-channel (or the inter MBAN) interference is the dominant problem. When a dominant radio system such as WLAN with much stronger transmission power or interference is present, we have provided methods to assist the proposed centralized and distributed interference management techniques, outlined in the first and second parts of current paper.

In order to make our proposed protocols feasible in real life applications, we propose to include the necessary signalling middleware for radio incumbent systems that are going to share spectrum with MBANs under future and emerging standards such as IEEE 802.15.6.

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Appendix A:

A.1. Measurement of interference inflicted from one sink on another:

It is assumed that the radio channel fading conditions are similar, when say for example, we migrate from the spectrum assignment $C1$ to the spectrum assignment $C2$. In this case, in its simplest forms the initial setup protocol for interference measurement is depicted in the following Figure 31.

A.2 Measurement of interference inflicted from sensors served by one sink on other sinks when network is live and operational:

1. Immediately before the start of the main transmissions, the sink1 identifies which sub-channel would be allocated to which sensor within the assigned spectrum.

2. Sink1 inform the other sinks that a test-transmit is about to happen within for that specific sensor configuration. The other sinks (in this example the

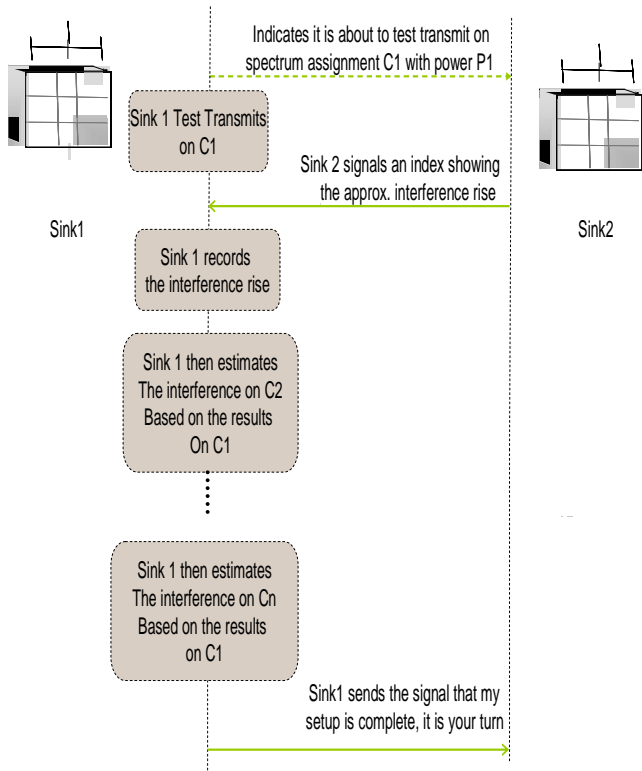sink2 and sink3), would go to the measurement and the listening mode.

3.

Figure 31 Setup Protocol for Interference Measurements, Third Approach

Then sinks replace each other as shown in the following Figure

3.   The Sink1 informs the sensors to transmit within the extra sub-chunk of the spectrum with current candidate modulation and coding scheme, and the assigned power as shown in Figure 33. The Sink1 would not decode the information within that specific test-transmission period.

4.   For that specific transmission attempt the sink2 and sink3 inform the sink1 of the rise on their interference levels as shown in Figure 35. The Sink1 records the value.

5.   Before the channel allocation process starts, the sink1 may attempt to do the similar process (Steps 1-4) for other spectrum sub-chunks and records the increased interference values.

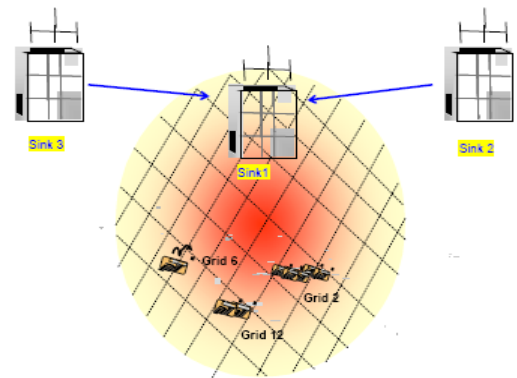The time diagram in Figure 35 summarizes of the proposed protocol:

Figure 32 Setup Protocol for Interference Measurements, Third approach (cont.)
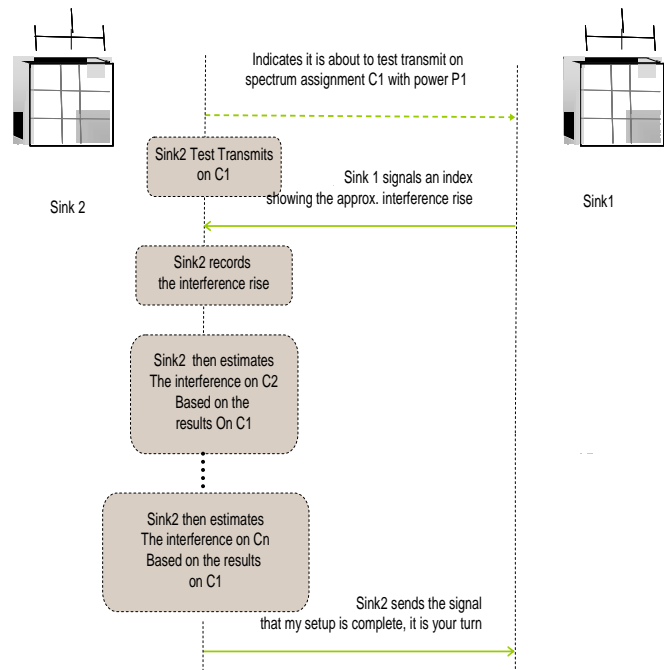

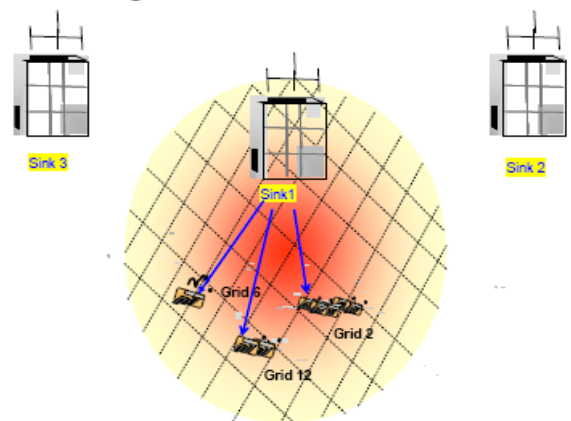Figure 33 Sensors are informed about the up-coming test-transmission

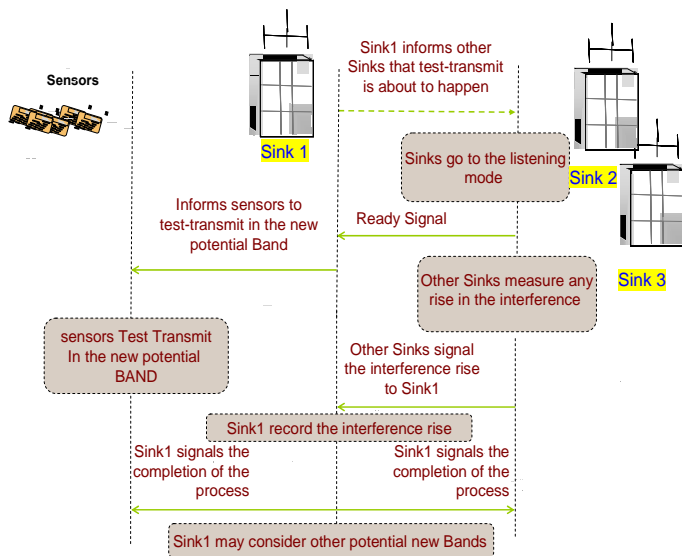Figure 34 SINK2 and SINK3 is inform SINK1 of their interference rise

Figure 35 Second approach for measurement of interference caused by sensors

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He was one of four thousand technologists/artists/scientists to be recognized in the "Cambridge Blue Book" 2005 edition and will feature in the 2007-08 editions. He holds/pending/has been granted more than 30 patents in different fields of wireless communications. Dr Abedi is currently serving as a member of Editorial Board for IET Journal Communications (formerly known as IEE Journal/Proceedings Communications). He has also served on the Session Chair and the Technical Program Committee member of a number of major conferences. Dr Abedi is a member of IEEE.